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Additive manufacturing is rapidly being explored as a means to achieve new design paradigms while enabling an effective means for production. A particular field of interest is heat exchangers. Through additive manufacturing, this family of components can be produced more directly as opposed to the traditional manufacturing and assembly techniques used to create heat exchangers. Based on this, research was conducted at the Applied Research Laboratory and the Center for Innovative Materials Processing through Direct Digital Deposition at The Pennsylvania State University to determine the viability of additive manufacturing for producing aerospace heat exchangers for naval air platforms. This report considers various heat exchanger types and designs, designs that may be applicable to additive manufacturing, conceptualization of a design for a liquid-gas heat exchanger that may be produced using additive manufacturing techniques, a manufacturing demonstration of such a design, and the evaluation of the heat dissipation characteristics of the notional heat exchanger.

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# Utilization of Additive Manufacturing for Aerospace Heat Exchangers

**Research Conducted for the Office of Naval Research Under the Enabling Additive Manufacturing Technologies for Industry Insertion Project**


**Research Conducted by:**

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## Abstract

Additive manufacturing is rapidly being explored as a means to achieve new design paradigms while enabling an effective means for production. A particular field of interest is heat exchangers. Through additive manufacturing, this family of components can be produced more directly as opposed to the traditional manufacturing and assembly techniques used to create heat exchangers. Based on this, research was conducted at the Applied Research Laboratory and the Center for Innovative Materials Processing through Direct Digital Deposition at The Pennsylvania State University to determine the viability of additive manufacturing for producing aerospace heat exchangers for naval air platforms. This report considers various heat exchanger types and designs, designs that may be applicable to additive manufacturing, conceptualization of a design for a liquid-gas heat exchanger that may be produced using additive manufacturing techniques, a manufacturing demonstration of such a design, and the evaluation of the heat dissipation characteristics of the notional heat exchanger.

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# 1.0 Introduction

## 1.1 Problem Statement

Given the huge potential for additive manufacturing to improve performance, reduce cost, and decrease lead times, the United States Navy has developed a broad initiative in additive manufacturing, and an important component to this activity is the identification of challenges and solutions for successfully implementing additive manufacturing for critical naval applications. An important aspect of addressing these challenges is in the correct selection of components being considered for additive manufacturing. The potential of additive manufacturing is driven by the ability to reduce cost through decreased use of expensive material or reduced additive manufacturing cost when compared to traditional manufacturing methods, the potential to improve part performance through innovative designs that may be economically accomplished by additive manufacturing, and reduced lead times through use of digital product and process data. Part selection is an extremely important aspect of meeting these requirements. The ability to fully exploit the process is dictated by the nuances found within a parts family. Hence, this program was directed at formulating an initial assessment for using additive manufacturing for producing complex, aerospace heat exchangers for naval air applications. The various issues regarding the use of additive manufacturing for these types of components will be discussed in greater depth in their respective sections of the report.

### 1.2 Objective

The objective for this project can be divided into four subcategories. This includes a review of aerospace heat exchangers, identification of gaps in the current additive manufacturing technology for this application, design of a notional heat exchanger based on additive manufacturing technologies, and a manufacturing demonstration and evaluation of the notional design.

The first of these objectives was a review of aerospace heat exchangers and prior activities regarding additive manufacturing of these components. This discussion also includes the identification of existing capabilities, as well as limitations to produce complex, thin walled shapes and fine internal passages, found in premium heat exchangers. The review also encompasses the evaluation of current additive manufacturing equipment that may be applicable for producing heat exchangers.

The second objective for this project was the identification of possible gaps in the current technology. The purpose of this was to explore methods that may be used for increasing quality and improved reliability during the manufacturing of heat exchangers. This would ultimately allow for a more consistent product and increased uniformity. The identification of gaps in the current technology would also address the apprehension that the Navy faces in planning for the insertion and implementation of additive manufacturing.

The third objective was to develop a design for a notional aerospace heat exchanger based on additive manufacturing. The design would be based on the knowledge acquired during the earlier activities, along with an improved understanding of heat exchangers, and elements of design for additive manufacturing. Exploratory designs would be developed based on the identification of sub-functions related to manufacturing and potential performance improvements enabled by additive manufacturing. As part of this effort, a morphological chart would be developed to aid in developing the conceptual design. The final objective of the project was the technical demonstration involving the fabrication of the notional heat exchanger using additive manufacturing, along with testing of the device to determine its heat dissipation characteristics.

# 2.0 Review

## 2.1 Aerospace Heat Exchanger Discussion

Heat exchangers can be found in a wide spectrum of applications, ranging from the food to automotive industries. They are used to either cool or heat fluids, and do so by transferring heat between two fluids, many times being a liquid to a gas medium. There are many different features of heat exchangers that fall into various categories, such as flow types and enhancements.

There are three main fluid flow types: parallel, counter, and cross flow. These flow types are illustrated in Figure 1. Due to thermal properties, each of these flows will affect the heat transfer rate that may be achieved. This is illustrated in Figure 2, which shows how the logarithmic mean temperature gradient changes over time depending on the type of flow. The efficiency of the various heat exchanger designs may thus be viewed based on the logarithmic mean temperature of the flux, dictated by the difference between the two heat exchanger mediums at a given location, over time. The starting temperatures between the two mediums for heat exchangers using a cross flow or parallel flow arrangement are initially far apart, but since they converge over time the fluid that is being cooled, or heated, experiences less of a change and results in lower heat dissipation over time. This occurs to a lesser degree with parallel flow heat exchangers. In contrast, in heat exchangers utilizing a counter flow arrangement the temperature differential is initially large and remains relatively constant over time. This allows for a greater thermal differential between the two mediums during operation, making the counter flow heat exchangers very effective. There are a few, special circumstances when a counter flow design is the most efficient, but this design is usually employed due to ergonomic considerations.

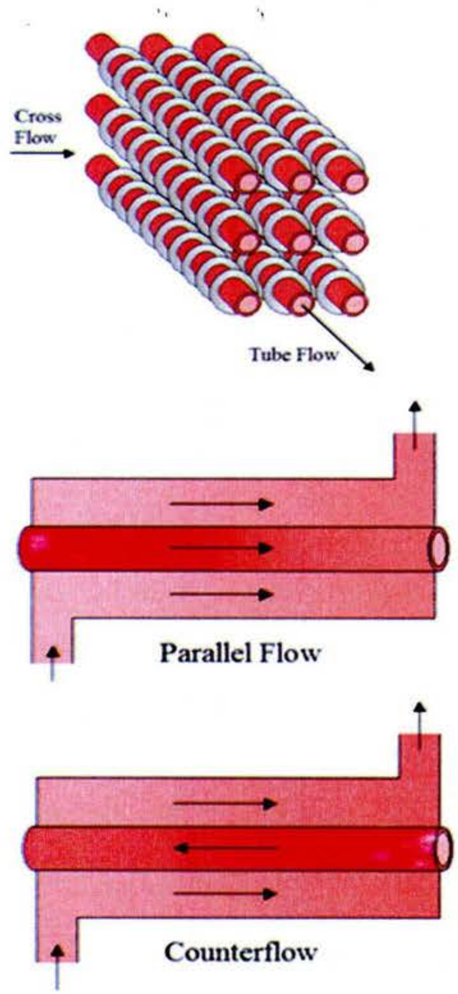



Figure 1: Schematic of the various flows using for heat exchangers.

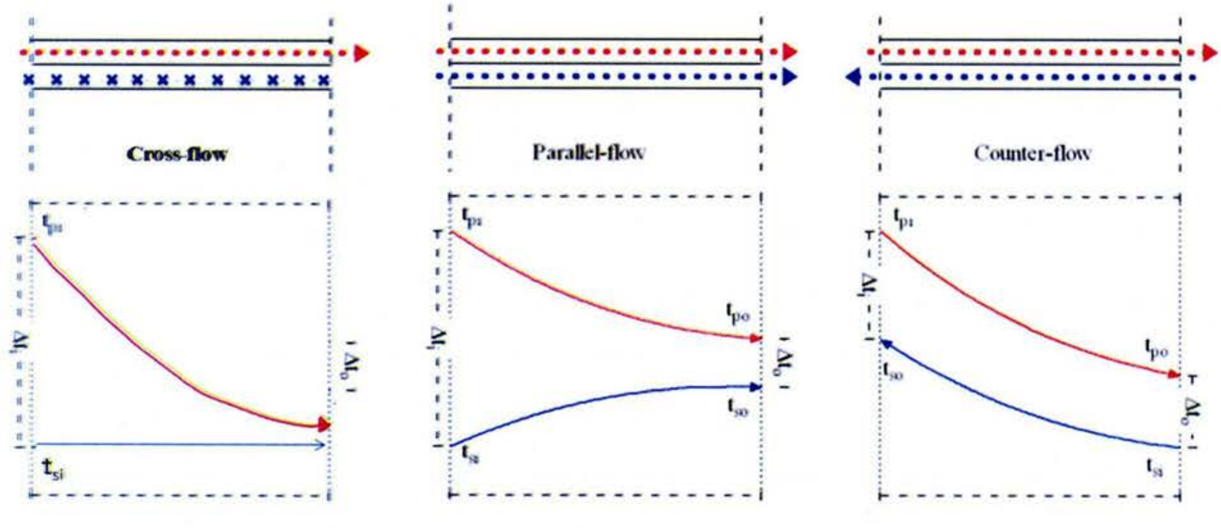



Figure 2: Logarithmic mean temperatures as a function of time for different flows.

The most logical features to explore for a heat exchanger design that may be produced, and potentially enhanced, by additive manufacturing are baffles, fins, and tube inserts. Baffles are used to support the tube, maintain the tube spacing and direct the flow of fluid in a desired pattern through the shell side. Adding baffles to a tube in an efficient manner can drastically change the heat transfer rate. For example, adding baffles to a single pass, counter flow design can change the flow to multi-pass, cross flow, drastically changing heat transfer. An example of this can be seen in Figure 3. Not only does the introduction of baffles provide more structural support, but they also allow for greater heat transfer due to an increase in the amount of cross flow paths. Much like flow types, baffles can be modified to change the degree of heat transfer to better match the intention of the heat exchanger. Figure 3 also shows a few of the most popular baffles used in industry. The single segmental transverse baffle can be used to support tubes during assembly and operation and to direct the fluid in the tube bundle at right angles in order to achieve higher heat transfer coefficients. The double segmental transverse baffle is much like the single segmental transverse baffle in that it assists heat transfer from the high shell-side, and it doubles the fluid stream line of its single counterpart. The doughnut and disk type baffles have small perforations between tube holes to allow a combination of cross flow and longitudinal flow and results in a lower shell-side pressure drop. The combined flow leads to a slightly higher heat transfer coefficient compared to that of pure longitudinal flow. In addition, doughnut and disk type baffles minimize tube-to-tube temperature differences. Because of these attributes, doughnut and disk baffles are primarily used in nuclear heat exchangers. Lastly, the longitudinal baffle's main purpose is to control the overall flow direction of the shell fluid, such that a desired overall flow arrangement of the two fluid streams is achieved. The degree of transfer of the baffle is controlled by its surface area, support strength, tube spacing, and the flow type of the heat exchanger.

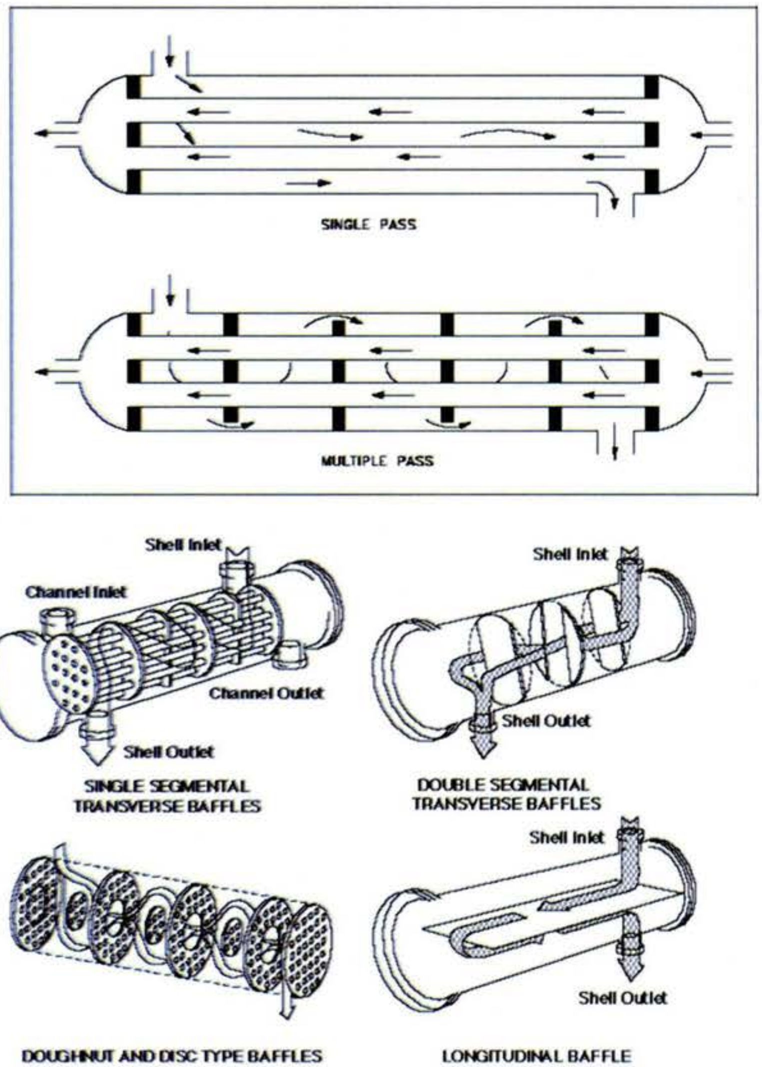



Figure 3: Schematics illustration two primary baffle flow conditions and various types of baffles used in heat exchangers.

Fins are another important feature of heat exchangers using liquid and gas mediums. Fins provide increased surface area for tubes carrying the liquid, leading to a greater rate of heat transfer by convection of the gas. The fins allow liquid-gas heat exchangers to attain a more specific heat transfer rate based on a given flow type design. Fins are useful because in many instances it is not economical or feasible to alter the operating temperature differential or change materials of construction. Increasing the surface area of fins achieve the same function at a more reasonable price. There are four main types of fins which are used in heat exchangers, and these are illustrated in Figure 4. Plain fins are simple straight-finned designs that can be rectangular or triangular. The Herringbone design is where the fins are placed sideways to each other to provide a weaving gas path. Serrated and perforated fins consist of perforations in the fins to alter flow distribution and improve the heat transfer rate. Much like tube inserts, fins also enhance heat transfer rate but are recognized more for reducing mitigation of the systems over time.

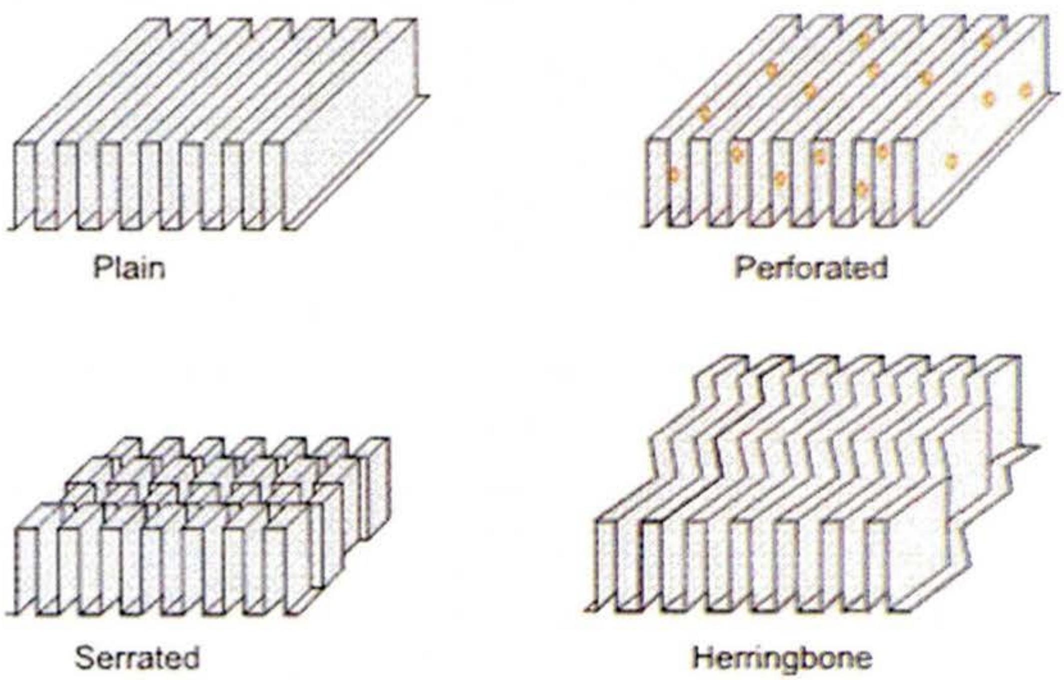



Figure 4: Schematics of the various types of fins used in liquid-gas medium heat exchangers.

### 2.2 Additive Manufacturing Technology

In addition to understanding the characteristics of the heat exchangers, it is also important to understand the additive manufacturing process that may be potentially used to produce heat exchangers. Because of the complexity of a heat exchanger and the potential to produce fine features, the additive manufacturing process that would most likely be used to produce these types of components is the laser based powder bed fusion (PBF) process, which is also referred to as selective laser melting (SLM), direct metal laser sintering (DMLS), selective heat sintering (SHS), and selective laser sintering (SLS). There is also a similar technique that utilizes an electron beam instead of a laser to melt a pre-deposited powder and is referred to as electron beam-based powder bed fusion. Shown in Figure 5 is a schematic of the laser-based powder bed fusion process showing how the laser is used to selectively melt pre-deposited metallic powdered in a chamber of inactive gas to form a fused layer. Many layers are selectively created to form a three-dimensional shape. The benefits and issues associated with producing the various types of heat exchangers using the powder bed fusion process is discussed in the following sections.

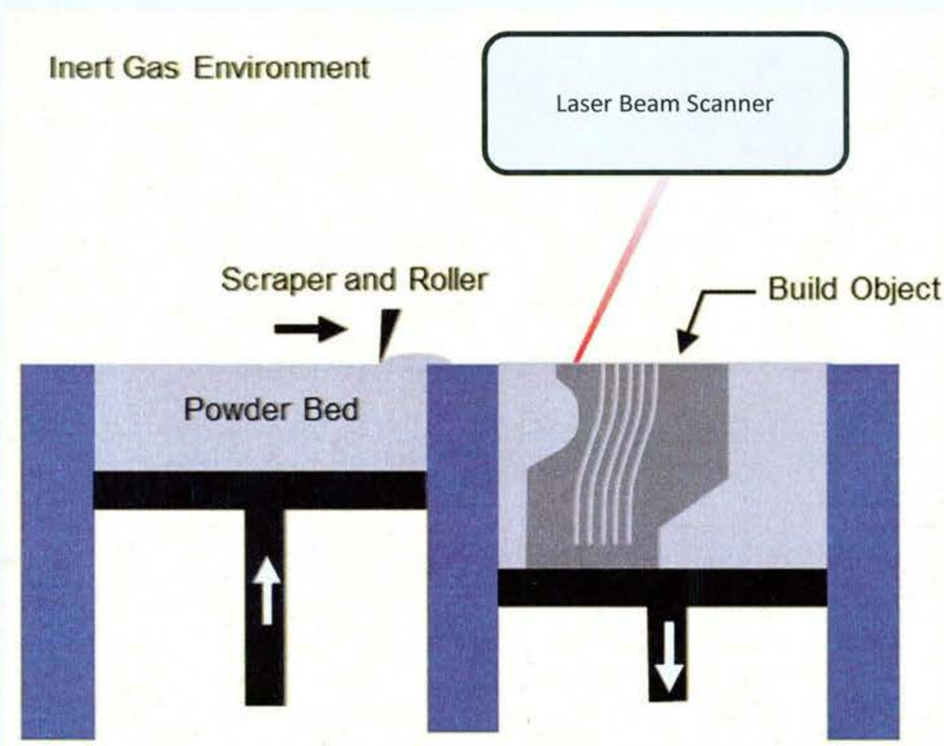



Figure 5: Schematic of the laser-based powder bed fusion (PBF) process.

## 2.3 Existing Capabilities of Heat Exchangers

Currently, the manufacturing of heat exchangers entail a long and expensive progression of subtractive (cutting and punching) and conjunctive (brazing) processes. In addition, the brazing process usually requires a complex arrangement of fixtures that involves significant labor and time. Brazed heat exchangers are typically of plate and fin design. These heat exchangers can be made very compact and have a very high heat dissipation rate. The base of the exchanger is made up of flat plates that are layered on top of each other creating air passages in between the plates where the hot liquid and cold liquid flow. Shown in Figure 6 are examples of two heat exchangers produced by brazing of plate and fins.

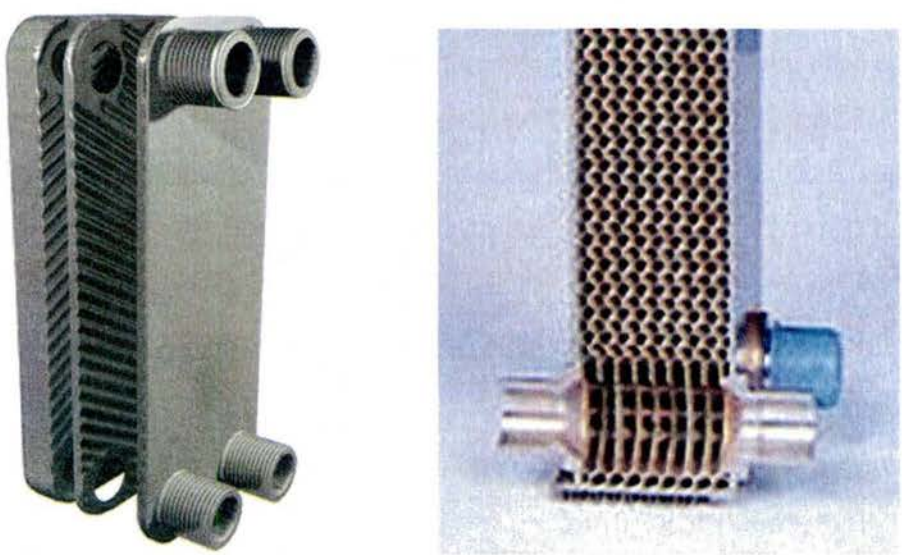


Figure 6: Two examples of brazed heat exchangers employing plate and fins.

Due to the way in which brazed heat exchangers are built they either run counter flow, as shown in the above figure, or by parallel flow. Brazed heat exchangers do not employ cross flow designs. The size of the heat exchanger can also be problematic. For example, due to the small passageways created for the compact size, the passages may easily clog. The problem is compounded due to the fact that since the passages are so small, they are difficult to maintain, and hence, cleaning is performed manually. Lastly, there is no design flexibility with a brazed heat exchanger. Because of the complexity of the traditional manufacturing process for brazed heat exchangers, little design flexibility is available and the vast majority of current heat exchangers reflect the same rectangular shape.

Another common design is a tube heat exchanger. These heat exchangers are also referred to as shell and tube heat exchangers, and examples of this type of design can be seen in Figures 7 and 8. Shell and tube heat exchangers are made up of a variety of tubes in which liquids or air pass through the tubes. Either the tubes carry two different liquids to exchange heat or air can enter the shell to cause exchange of heat within the tubes. Baffles may also be used to direct the fluid to create a cross flow exchange in shell and tube heat exchangers.

There are a few advantages to shell and tube heat exchangers over plate and fin heat exchangers. One is that tube heat exchangers are more economical to produce. They can also be placed in systems that operate at higher temperatures and pressures. Unlike brazed heat exchangers, clogs and leaks can be inspected for and fixed when they occur. Various flows are also available for this type of heat exchanger and there is greater ability to customize the heat exchanger design.

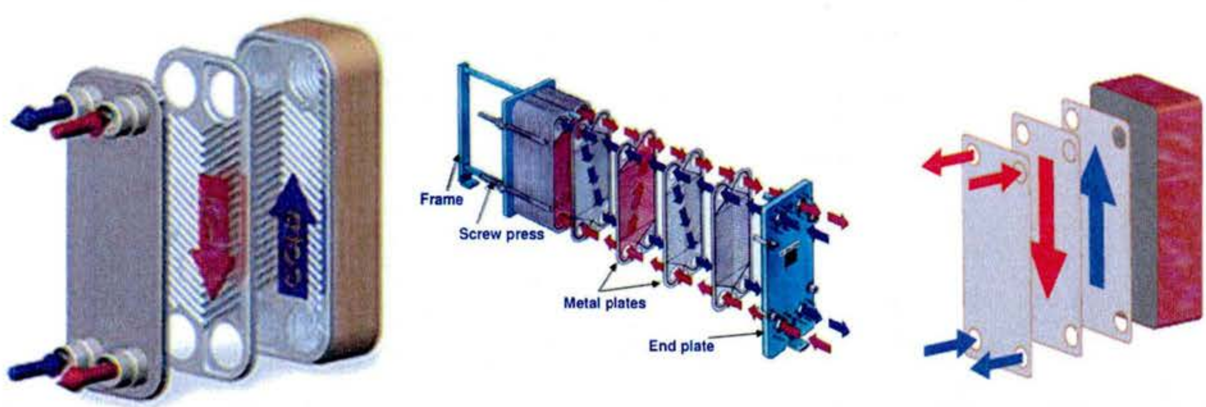



Figure 7: Schematics showing common flow for shell and tube brazed heat exchangers.

Figure 8: Photographs of two examples of tube and shell heat exchangers.

There are also detractions to a tube heat exchanger, since it are not as efficient in heat transfer as the plate and fin design. Shown in Figure 9 is a tube heat exchanger having a cross flow arrangement. Because of its design, the tube heat exchanger is also significantly larger that a shell and tube arrangement for a given heat dissipation rate. Lastly, once the heat exchanger is defined within its design constraints, it is very difficult to increase its size in order to attain a higher working capacity.

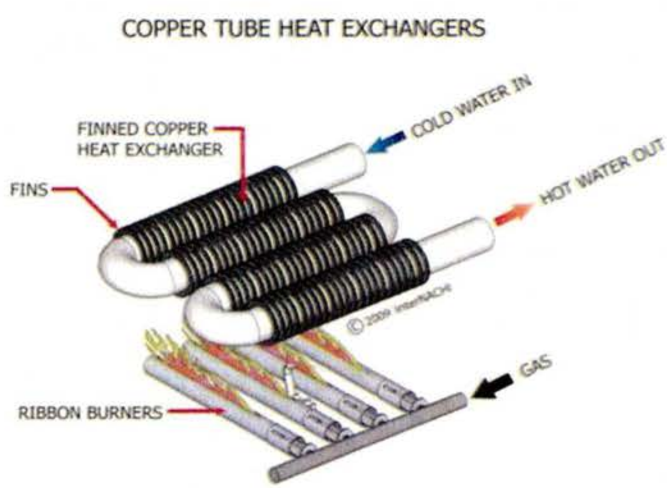



Figure 9: An example of a cross flow tube heat exchanger.

### 2.4 Existing Capabilities of Additive Manufacturing

Opposed to brazing, additive manufacturing provides a means of achieving fine, planar structures and features, and boundaries, as well as complex internal fluid channels. The benefits of being able to build hollow structures with additive manufacturing may allow higher design complexity that may increases performance, as well as broaden the application range due to higher strength-to-weight ratios. These complex designs can be made with a favorable surface area, leading to the manufacturing of smart, efficient heat exchangers.

A review of the literature revealed that aluminum alloys appears to be the most commonly used material for heat exchangers due to its high thermal conductivity relative to most other metals. Other metallic materials that are used includes stainless steel for operations at higher temperatures and corrosive environments, and nickel-based alloys that are used for operation at very high temperatures. Stainless steel and nickel-based alloys exhibits higher density than aluminum alloys, which results increased weight, but may operate at temperatures well above 300 °C, the maximum operating temperature for aluminum. Copper has also been used for special heat exchanger applications but is not considered a viable material for aerospace applications.

### 2.5 Existing Limitations of Additive Manufacturing and Heat Exchangers

Although the mechanical and thermal properties of metals makes them the ideal material for heat exchangers, powder bed fusion processes, be it laser-based or electron beam-based, result in a relatively rough as-built surface which could very likely influence fluid flow in internal channels. The surface roughness achievable with laser-based powder bed fusion is on the order of 12.5 $\mu$m Ra or 500 micro inch Ra. However, honing may be used to significantly increase surface finish of internal channels. When internal structures of fluid channels are produced using the powder bed fusion technique, the design of the feature must consider the need of internal support structures that are sacrificial but used to support the molten pool during the build.

Support structures are created by utilizing processing parameters that only partially sinter the powder particles, thus allowing them to be easily removed after the process. However, unfused powder from the support structures may pose significant problems for removal from complex designs. An example of support structures being employed additive manufactured parts produce using laser-based powder bed fusion is shown in Figure 10. A method that is typically used to eliminate the need of support structures is to maintain the horizontal overhang of hollow structures to be greater than 40 degrees. This may impose design constraints that must be considered, such as the use of high aspect ratio cross-sections versus circular hollow channels. Another important characteristic of heat exchangers that sets additive manufacturing apart from other processes is its ability to produce thin-walled features. Although the exact wall thickness depends on a multitude of parameters, thin walls on the order of 200 um may be created with reliable structural integrity.

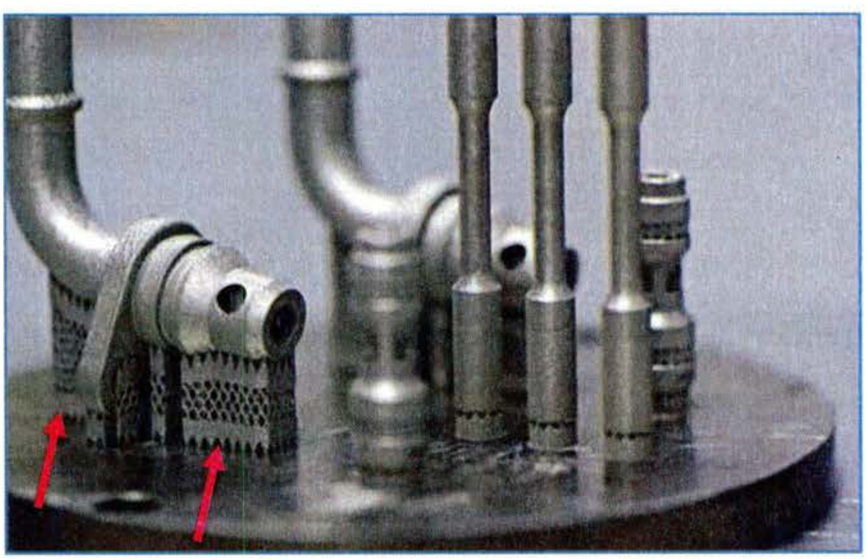


Figure 11: Examples of support structures, shown by arrows, used during the additive manufacturing process to support overhangs (Courtesy of CIMP-3D Penn State).

## 2.6 Equipment Capability

There are various options for powder bed systems available today, and the more common manufacturers include EOS, 3D Systems, Concept Laser, MTT Renishaw and Arcam. All of the above systems utilize laser-based powder bed fusion except for the Arcam system, which is electron beam-based. In actuality, all of these systems use a basic configuration that includes: a powder bed coating system, mirrors and galvanometers (laser-based) or an electromagnetic coil arrangement (electron beam-based) for two-dimensional scanning of the heat source on the powder layer, stages that decrease the build plate and increase the powder reservoir to accomplish each build layer, a processing chamber that provided an inert gas or vacuum environment (the vacuum is used for the electron beam-based system), and a computer controller. Lasers used for the laser-based systems provide between 200 and 1,000 W of output power, and the electron beam based system utilizes approximately 1,000 W of output power.

One means of characterizing these systems is based on the build volume, which range from approximately 200x200x200 mm to 350x350x350 mm. Several manufacturers produce systems having build envelopes in the 350X350x350 range and include the EOS M350, the 3DSystems ProX320, and the Arcam q20. The Concept Laser X line 1000R has by far the largest build volume with a build envelope of 630x400x500 mm, serviced by a 1,000 W laser. The chart shown in Table 1 provides a comparison of the major dimension and features of various powder bed fusion systems, and Figure 12 shows photographs of several system.

Table 1. Features of various powder bed fusion systems.

| Company | Machine | Maximum Build Dimensions (mm) | Laser Type | Maximum Power (W) | Minimum Layer Thickness | Production Speed |
|---|---|---|---|---|---|---|
| 3D Systems | ProX320 | 320x320x350 | Fiber | 500 | | |
| Concept Laser | X Line 1000R | 630x400x500 | Fiber | 1000 | 30-200 um | 10-100 $cm^3/h$ |
| MTT Renishaw | AM250 | 250x250x300 | Fiber | 200 or 400 | 20-100 um | 5-20 $cm^3/h$ |
| ARCAM | ARCAM q20 | 350x380x500 | Fiber | 3000 | 180 um | 4000 $cm^3/h$ |
| EOS | M290 | 280x280x300 | Fiber | 400 | 20-40 um | |
| EOS | M350 | 350x350x350 | Fiber | 400 | 20-40 um | |

3D System ProX320

3D Systems ProX300

Concept Laser Xline 1000R

EOS M290

ARCAM arcam q20

MTT Renshaw AM250

Figure 12. Photcgraphs of several powder bed fusion systems for additive manufacturing.

## 3.0 Gaps in Technology

Based on a review of the literature, gaps in technology were identified that may hinder adoption of additive manufacturing for these applications. These gaps were primarily identified through a recent report by the National Institute of Standards and Technology. A list of current challenges defined within this document, and cultivated through a broad industry survey, is shown in Table 2. Although these deficiencies currently exist, the rapid development and socialization of additive manufacturing technology is helping to address these challenges to reduce the barriers for implementation of the technology.

Based on the review, one particular gap in technology was considered especially relevant to this application. Since potential heat exchanger designs for additive manufacturing would entail complex geometries and fine-scale features requiring complete sealing, the reliability of the process for producing high quality parts would be paramount. Although there is significant research being directed at sensing of important process parameters and conditions during the powder bed fusion process, no commercial systems are available today that possess the capability to monitor and report on the health of system or consistency of the process to a degree required to achieve high reliability.

One means of addressing process reliability and overall part quality is through the use of sensing and control technology. Current research in this area is exploring a wide range of sensors and analysis techniques in this regards. This includes: the use of high resolution optical imaging of each layer to continually ensure consistency of the recoating operation and the fusion operation during the process, the use of IR sensors to capture thermal images locally and globally during the build process, employing various sensors to continually measure specific response characteristics during the process, such as acoustic emission, reflected energy intensity, and emission spectroscopy. Advanced research in this area has focused on the use of a suite of sensors that enable various response signals to be correlated with various process anomalies. The results of this research shows promise in having commercial capabilities for measuring process uniformity in the near future; however, the use of this data for controlling the process has not progressed at the same rate. This has primarily been due to the lack of detailed process understanding and inability to easily access the process control system for much of this equipment

One method that is being exploited for influencing the results of the additive manufacturing process is the use of numerical modeling for simulating and managing thermal distortion, which not only may result in loss of dimensional tolerances but also may affect part quality through recoater interference and the formation of flaws or cracks. Thermal distortion during the process can cause significant deformation, such that the intermediary build may deform off of the build plate and result in uneven coating of subsequent powder layers or complete failure of the system to recoat. The perturbations in recoater consistency has been found to be a major source of variability in part quality, which would be exasperated for designs having fine, complex features.

Another gap in technology with current additive manufacturing systems is the lack of interchangeability of powder feed stock. The processing systems and the process parameters, which are usually provided by the system supplier, have been formulated to work with a specific powder feed stock that represent the atomization process for a particular powder supplier. Although it is possible to replicate a powder size distribution based on mean particle diameter, diameter at 10%, and diameter at 90%, minor changes within a similar distribution may have an effect on processing, and ultimately, part quality. The use of "non-standard" powder material on a specific powder bed fusion process may require modifying "standard" process parameters for that material, and given the complexity of generating the large parameter set for the powder bed fusion process, many organizations are content in using standard powder provided by the system supplier. This is satisfactory if the manufacturer is willing to pay a premium of up to 100% for the powder and the powder alloy that is available by the system supplier provides adequate properties.

Table 2. Barriers and challenges for broad adoption of additive manufacturing technology (excerpted from a report by the National Institute of Standards and Technology).

| Barriers and Challenges for AM Qualification and Certification (• = one vote) | |
|---|---|
| **Standard and Protocols** | |
| *High Priority* | • Non-standard guidelines for qualification and certification •••••••••••••<br>o Defining sufficient type and quantity of guidelines<br>o Wide variations in machines and end users<br>o Limited ASTM qualification and certification guidelines for AM machine components<br>o Adherence to standards and proof of compliance are inconsistent<br>o Addressing unique specifications with industry-wide common standards<br>• Lack of standards based on round-robin testing (how to build) ••••••••••••<br>o No test protocol for materials testing and inconsistent reporting of results<br>o Incomplete part inspection and test standards<br>o Non-standard ratio of new/used powders and associated test protocols |
| *Medium Priority* | • Lack of standard build parameters on different machines; no adoption of a baseline set of standard and open application programming interfaces (APIs) and file formats among vendors ••• |
| *Low Priority* | • Complicated part repair due to complexity of materials and geometry, inconsistent automation, and lack of ASTM part certification standards<br>• Lack of vector hatch and mask standards (e.g., ASTM, descriptive standards)<br>• Difficulty of standards development (e.g., long, costly, technical work, volunteer work, intellectual property limits) •<br>o AM is not fully commercialized (i.e., not all technology is mature enough for standards)<br>o Non-standard AM systems hardware<br>• Incomplete post-process standards/specifications (e.g., internal, surface roughness, and measurements) •<br>• Lack of top level standards for dimensioning across machines •<br>• Lack of standards for AM materials linked to process (e.g., TI-624)<br>• Updating the OSHA material safety data sheet materials standards for AM<br>• Lack of industry standard materials specifications due to limited access to vendor data, no 3rd party ratings, no means to create reliability certification scorecards |
| **Inspection, Test, and Measurement Methods** | |
| *High Priority* | • Inadequate feedback sensors and data acquisition/measurement methods ••••••••••••<br>o Lack of in-situ measurements for real-time process control<br>o Lack of open loop/closed loop control systems for AM<br>o Inability to modify AM systems and materials due to IP ownership and need to adhere to maintenance and warranty requirements<br>o Creating methods to produce actionable information from data |
| *Medium Priority* | • Deficient feedstock-specific standards/specifications (e.g., vaporization and properties) •••<br>o Lack of standard artifacts to test microstructure (e.g., custom-design microstructure) |
| *Low Priority* | • Limited methods for characterization of complex materials, including multi-materials, multi-components, multi-functional materials, orientation-specific factors, and functions of process and build parameters • |
| **Data Challenges** | |
| *High Priority* | • Lack of shared, usable data in a 3rd party repository •••••••••<br>o Using parts improperly based on limited data, history, and/or metadata<br>o New data is not collected or shared<br>o Inability to correlate data<br>o Ability to produce materials based on geometric differences |
| *Low Priority* | • No central standard database for materials properties (e.g., high temperatures and mixed materials) |

## 4.0 Identification of Companies

The review of the literature had indicated that additive manufacturing was currently being explored globally for various application, and also being investigated for heat exchangers. One portion of this community is focused on developing new designs for heat exchanger that may be produced using additive manufacturing, and these conceptual designs dramatically depart from the traditional shell and tube.

Various companies were identified based on their research focus and history with additive manufacturing; however, detailed assessments were conducted on three organizations. One company in the U.S., General Electric Corporation, was considered based on its strong emphasis on implementing additive manufacturing for an existing aerospace product, the LEAP engine nozzle; while two additional companies are discussed as examples of small design firms that have embraced additive manufacturing and have interest in heat exchangers. These two companies were HiETA Technologies Limited and Plunkett Associates.

General Electric (GE) is pushing the boundaries of additive manufacturing and is close to scaling additive manufacturing to full production. GE's main use for additive manufacturing is within its aerospace division. The company has developed a design and additive manufacturing process for fuel nozzles for their jet engines that promises to improve performance and reduce manufacturing cost over the traditional nozzles, and have several other potential products identified for additive manufacturing. Shown in Figure 13 is a photograph of GE's LEAP nozzle designed to be produced through laser-based powder bed fusion process.

GE has been at the forefront in the United States in terms of developing the additive manufacturing process for production. The total investment in research and development funds within GE exceed 50 million dollars per year, and in the next five years, GE plans on tripling the size of their current additive manufacturing laboratory, while installing two facilities for producing production parts.

Figure 13: Photograph of GE LEAP engine nozzle produced using the powder bed fusion additive manufacturing process.

HiETA Technologies Limited is a UK company, with expertise in design, additive manufacturing, and thermal management, focused on developing designs for products that may be produced using additive manufacturing, and one area of interest is heat exchangers. Because their designs have been formulated specifically to exploit additive manufacturing, specifically the laser-based powder bed fusion process, HiETA heat exchangers look dramatically different from traditional heat exchangers. Having a strong background and understanding of the additive manufacturing process, HiETA has developed designs that utilize the inherent capabilities of the powder bed fusion process to improve functionality of the product. Their design typically consists of intricate curves and complex features, which is an efficient means for creating highly efficient, light-weight systems, while also being able to adapt a design to challenging three-dimensional spaces where an aerospace heat exchanger may be placed. Shown in Figure 14 are three examples of components designed by HiETA for thermal management that were produced using additive manufacturing. It is believed, based on their capabilities, that HiETA has not made available to the literature their advanced designs.

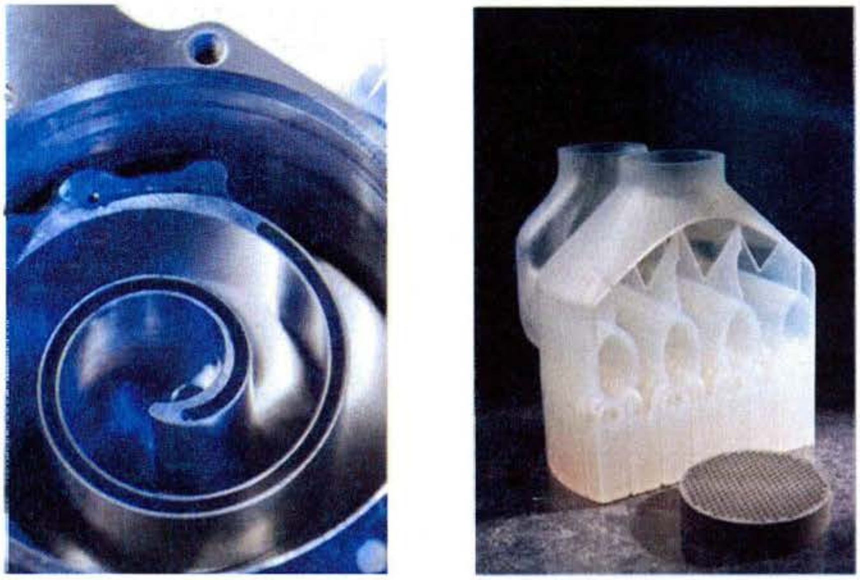


Figure 14. Three notional parts designed by HiETA for thermal management and to be produced through additive manufacturing.

Plunkett Associates is also a UK company focused on design but with a wealth of experience in additive manufacturing. Plunkett Associates are involved in several projects directed at improving heat dissipation through novel designs. Shown in Figure 15 is an example of a notional heat exchanger funded by the UK government under the SAVING Program. The figure shows the complex internal cavity and design of the completed part representing an aluminum heat exchanger built as a single components using the powder bed fusion process. The liquid to liquid heat exchanger was designed to improve the efficiency of the device through unique features available through additive manufacturing, while minimizing support structures. The resultant design incorporated distinctive flow circuits that enabled flow paths for the liquids that provided continuous and consistent heat transfer. Plunkett utilized computational fluid dynamics in conjunction with the design freedom available with additive manufacturing to create an efficient heat transfer device. The final design is illustrated in the photograph of the final part shown to the left in Figure 15.

In addition to the examples discussed above, significant interest in producing novel designs are being pursued in academic and research institutions. In many instances, the designs are being developed to demonstrate the ability of the process to produce complex shapes and features with little attention to rigorous analysis. Examples of complex components produced using powder bed fusion additive manufacturing based on these designs are shown in Figure 16.

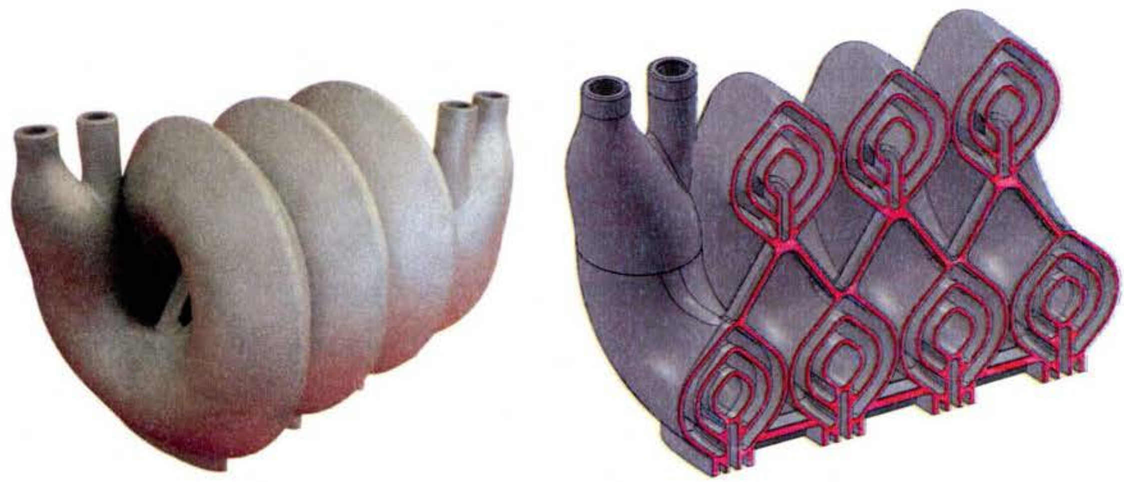


Figure 15. Example of an advanced aluminum liquid-liquid heat exchanger design by Plunkett Associates to be produced through additive manufacturing.

Figure 16. A few examples of complex components produced using additive manufacturing representing advanced designs for heat dissipation.

## 5.0 Design Concept

Three heat exchanger concepts were generated using a design innovation process that employed the use of a morphological chart and associated Colburn Coefficient graph, which is shown in Figure 17. The morphological chart provides a method to generate ideas and concepts in a systematic manner, and the Colburn Coefficient is a means of correlating heat and momentum transfer, provided one factor is known. It is commonly used in design of heat exchangers. The morphological chart was used in conjunction with the Coburn Coefficient to anticipate efficiency of the notional designs, while also anticipating some level of producibility through additive manufacturing. However, it must be noted that the primary purpose of this analysis was to evaluate the concepts from a heat transfer standpoint that could be taken forward to a full design for additive manufacturing. Two of the concepts involved liquid to liquid heat transfer and the remaining concept involve liquid to gas heat transfer.

The first concept, which represented liquid to liquid heat transfer, is referred to as the Weave and is shown in Figure 18. It incorporates the cross flow type with incidental baffles. Simple fins and circular cross-sections were utilized for this concept; however, this would not limit the use of greater complexity in full design. The second concept, shown in Figure 19, is referred to as the Baffle Stack. It also involves liquid to liquid heat transfer, and like the Weave, it also uses cross flow. Although the baffles are incidental, similar to the Weave, the baffle design provides cross flow with the tubes being used to cool or heat the fluid. The style of fin may be easily modified with the Baffle Stack design; however, based on optimizing the Colburn coefficient for a particular Reynold's number, the herringbone fin would be the best selection. The third and final concept is referred to as the Radiator and represents a liquid to gas heat exchanger. The morphological chart and the concept for the Radiator is shown in Figure 20. This concept utilizes a high packing density of thin fins with a liquid channel that is elongated in cross-section. The liquid channel is weaved throughout the fins and they also have an undulating surface or herringbone patterns along the length of the fins. To some degree, the Radiator represents an evolution of the first two concepts, and also reflects the greatest consideration for complex shapes and features that may be possible through additive manufacturing.

| Sun funtions | Solutions | | | | |
|---|---|---|---|---|---|
| Flow Type | Parallel | Counter | Cross | | |
| Baffles | Single Segmental Transverse | Double Segmental Transverse | Doughnut and Disc | Longitudinal | Incidental |
| Fins | Plain | Perforated | Serrated | Herringbone | |
| Cross Section | Circle | Rectangular | Triangle | Diamond | Square |

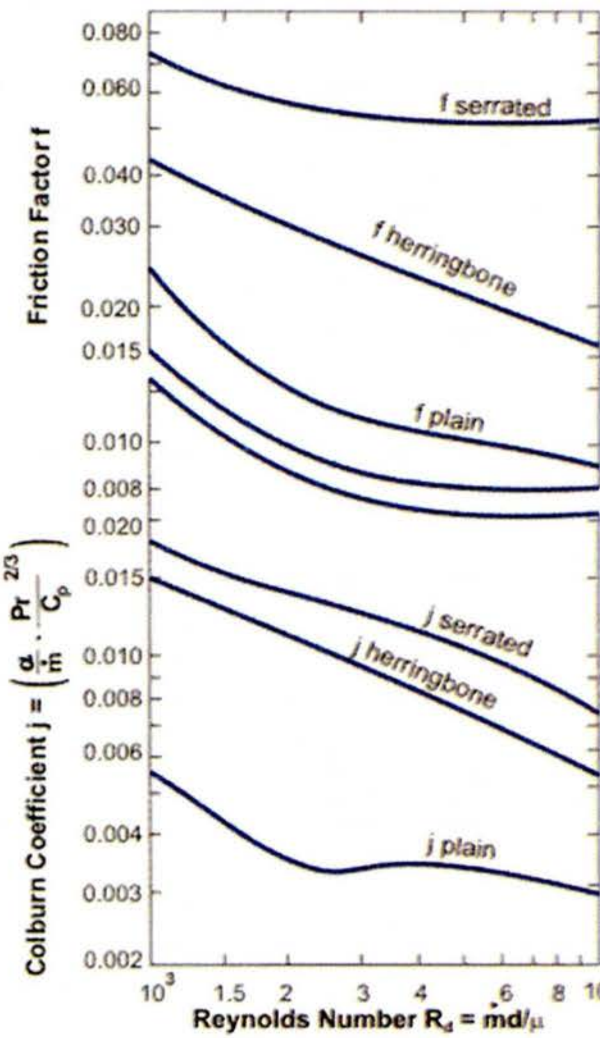



Figure 17. Morphological chart and Colburn Coefficient graph

| Sun funtions | Solutions | | | | |
|---|---|---|---|---|---|
| Flow Type | Parallel | Counter | Cross | | |
| Baffles | Single Segmental Transverse | Double Segmental Transverse | Doughnut and Disc | Longitudinal | Incidental |
| Fins | Plain | Perforated | Serrated | Herringbone | |
| Cross Section | Circle | Rectangular | Triangle | Diamond | Square |

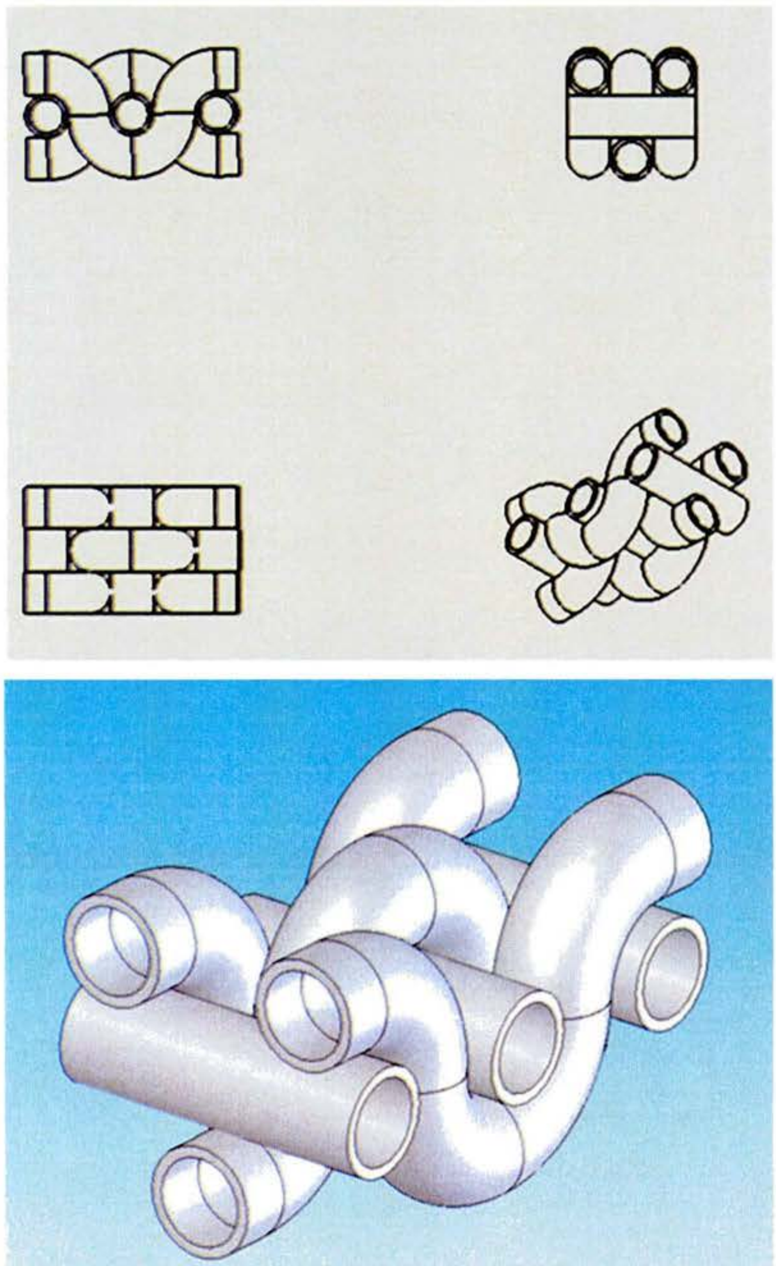


Figure 18. Morphological chart and design features for Concept 1, the Weave.

| Sun funtions | Solutions | | | | |
|---|---|---|---|---|---|
| Flow Type | Parallel | Counter | Cross | | |
| Baffles | Single Segmental Transverse | Double Segmental Transverse | Doughnut and Disc | Longitudinal | Incidental |
| Fins | Plain | Perforated | Serrated | Herringbone | |
| Cross Section | Circle | Rectangular | Triangle | Diamond | Square |

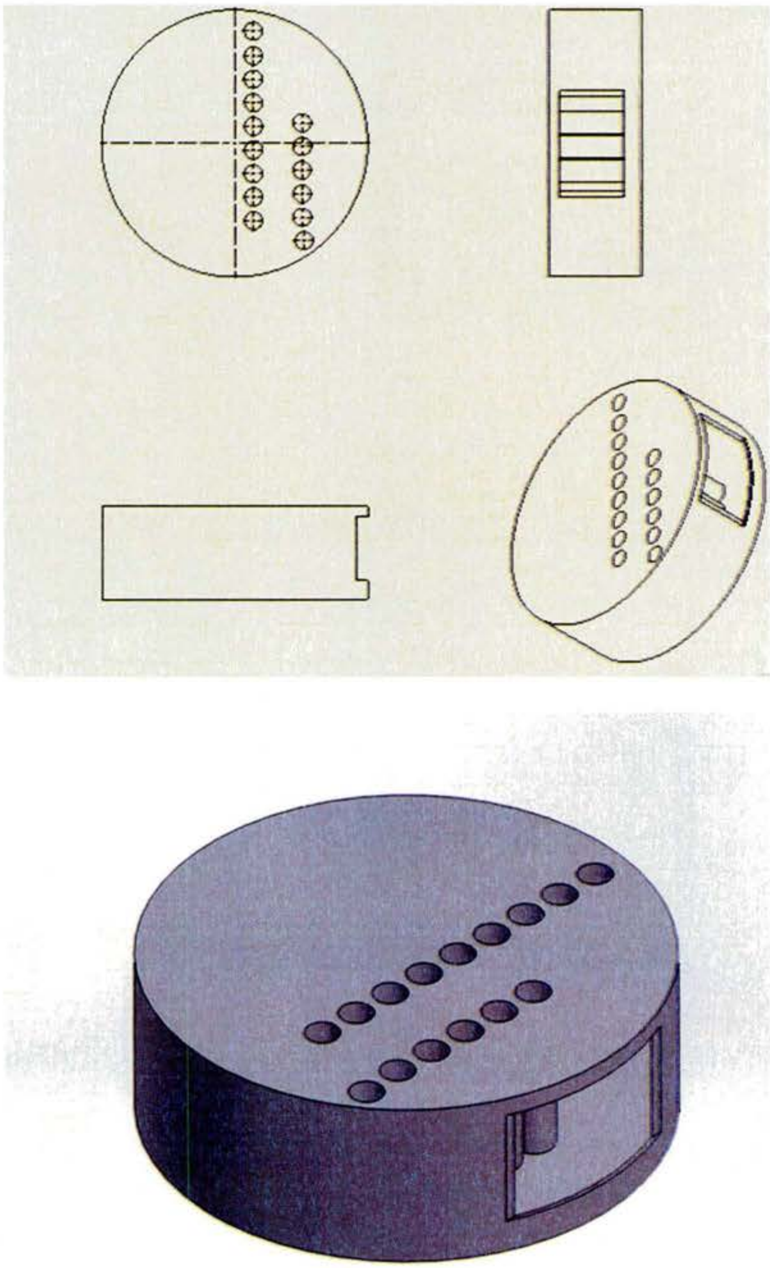


Figure 19. Morphological chart and design features for Concept 2, the Baffle Stack.

| Sum funtions | Solutions | | | | |
|---|---|---|---|---|---|
| Flow Type | Parallel | Counter | Cross | | |
| Baffles | Single Segmental Transverse | Double Segmental Transverse | Doughnut and Disc | Longitudinal | Incidental |
| Fins | Plain | Perforated | Serrated | Herringbone | |
| Cross Section | Circle | Rectangular | Triangle | Diamond | Square |

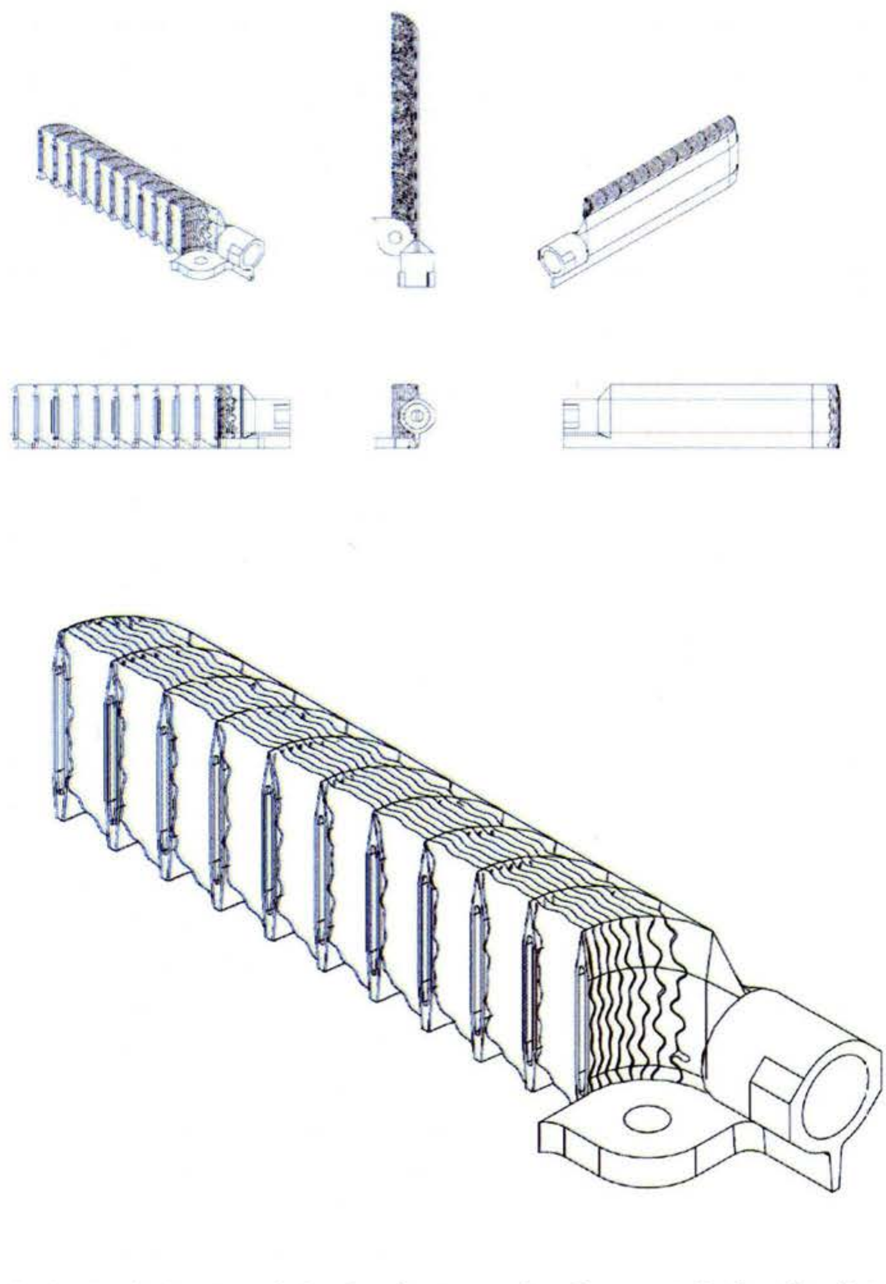


Figure 20. Morphological chart and design features for Concept 3, the Radiator.

The three concepts were generally screened using a Pugh selection process. The criteria for screening was based on the flow type, mediums, potential for effective heat dissipation, and the complexity of the preliminary designs. Although there was interest in further developing both a liquid-liquid and liquid-gas heat exchanger, available resources would only support one manufacturing demonstration. Hence, one concept was selected for further evaluation.

Since subsequent evaluations would involve a full design and manufacturing demonstration, complexity was given a greater weighting. This resulted in the Radiator being selected for additional trials. Reiterating, the Radiator concept described a liquid-gas heat exchanger having a serpentine channel for liquid flow that was surrounded by a high density of thin fins. The concept also enabled the simple extension of the liquid channel to increase heat dissipation. Based on the selection of the Radiator concept, a detailed design was conducted for producing the heat exchanger using the laser-based powder bed fusion process.

## 6.0 Design and Additive Manufacturing of Notional Heat Exchanger

The Radiator concept was selected for further refinement with the objective of developing a design that could exploit the use of additive manufacturing, specifically the laser-based powder bed fusion process, to produce a relatively complex device that could capture the basic attributes of a liquid-gas, aerospace heat exchanger. Based on Concept 3 above, the Radiator design was utilized as a starting point.

The basic concept had included a complex array of cooling fins and a serpentine liquid channel; however, several modifications and improvements were added to the concept. This included: adding several layers of the liquid channel along with added width of the cooling fins, design of an highly elongated liquid channel that would not require the use of internal support structures during the build, incorporation of small features within the cooling channel that would provide turbulent flow for greater heat transfer ability, and incorporating an undulating surface along the length of the cooling fins to increase surface area and improve heat transfer to the gas. A rendition of the final design is shown in Figure 21, and images of two of the improvements of the design are shown in Figures 22 and 23.

Figure 21. Final design of the Radiator used as the notional heat exchanger.

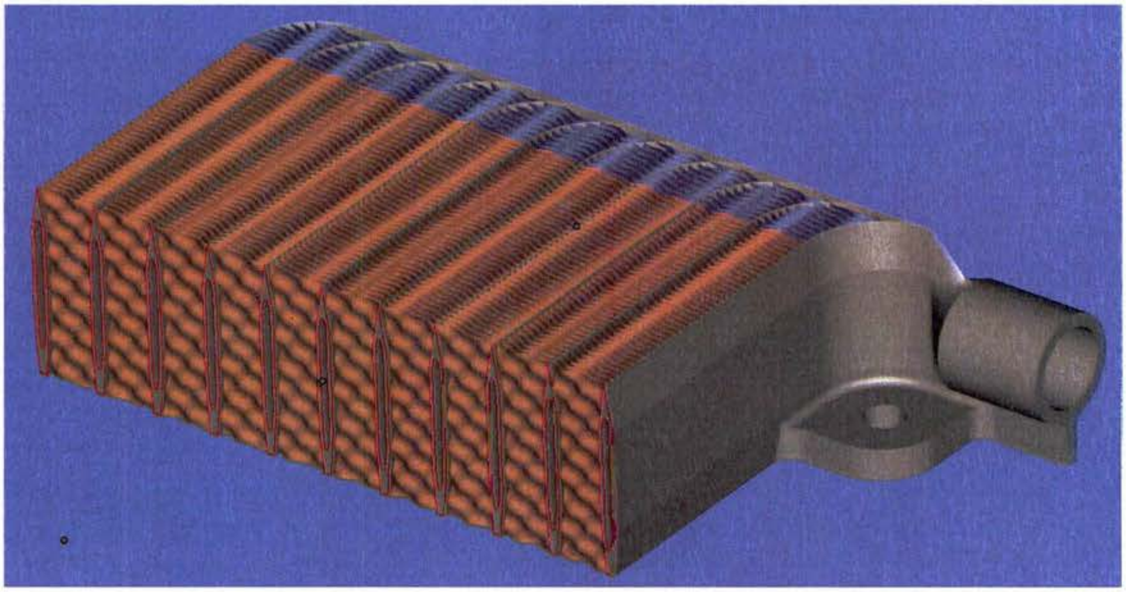


Figure 22. Design detail showing elongated liquid channel to eliminate internal support structures.

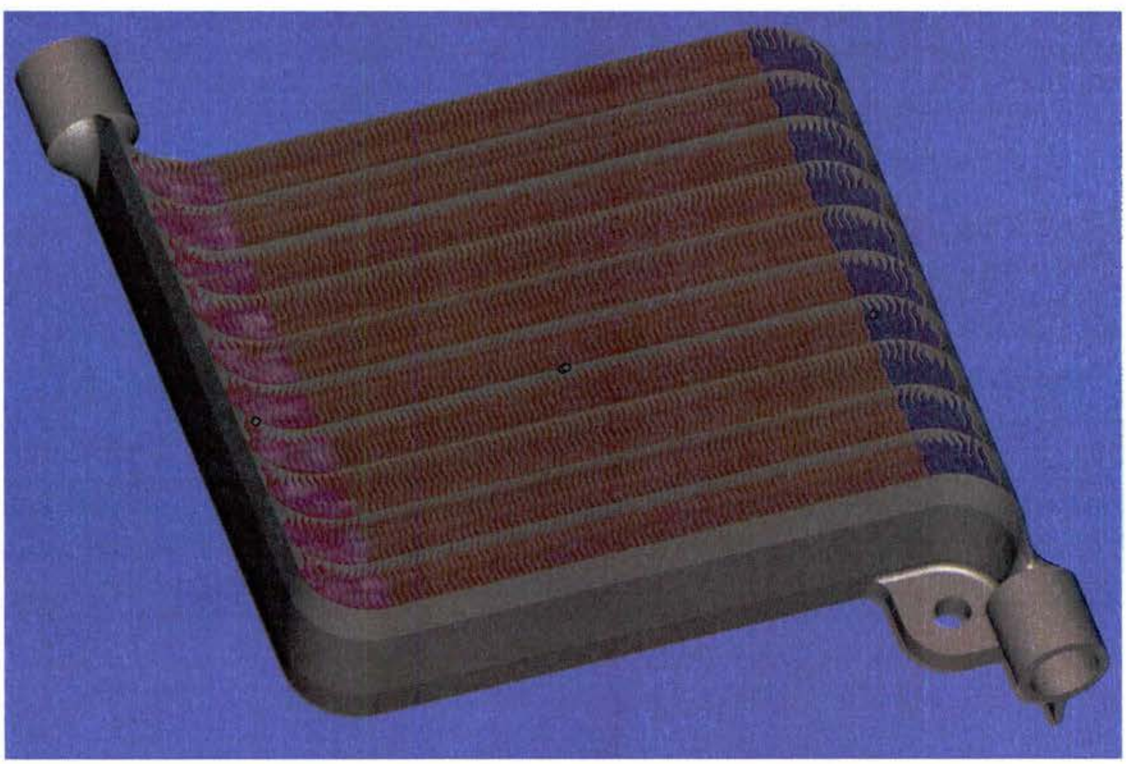


Figure 23. Design detail showing undulating fin surface for increased surface area.

The final design of the heat exchanger (shown in figure 21) was built using the EOS MINT 280 M laser-based powder bed fusion system. It was built as one solid component and, as mentioned, the elongated inner liquid channels were designed to be built without the necessity for support structures. The component was built in the horizontal position similar to the view of Figure 21, and a solid support structure was projected onto the aluminum build plate to act as a foundation. The heat exchanger was produced using the EOS aluminum alloy, which represented an Al-10Si-0.5Mg alloy.

The basic function of the heat exchanger was to allow the hot liquid to flow into the inlet of the heat exchanger, flow throughout the liquid channel causing heat to be dissipated by the cooling fins, and then exit the heat exchanger via the outlet. The inlet and outlet can be seen in Figure 21. The heat exchanger liquid channel was comprised of 11 paths connecting the inlet and outlet. The liquid channels were evenly spaced across the part. The undulating cooling fins were approximately 300 mm in width and spaced at intervals of approximately 400 mm. The exact dimensions of these features were not predetermined because support structure parameters were utilized to increase feature definition, and these parameters do not produce feature details that have been documented within the process specification. Shown in Figures 24 and 25 are photographs of the completed heat exchanger after post process solution heat treating and aging followed by removal from the build plate using electrical discharge machining (EDM). Post process solution heat treating was conducted at 530 °C for 5 hours followed by water quenching. The aging practice was 8 hours at 163 °C.

Lastly, as shown in the figures, the cooling fins run perpendicular to the liquid channel, which is indicative of a cross flow design. The design of the fins utilized a sinusoidal function to create the undulating pattern along the length and depth of the fins, which is similar to the herringbone style discussed earlier. Small features or "bumps" where also added periodically to maintain spacing and alignment of the fins so as to not impede gas flow. Shown in Figure 26 is a photograph of the completed aluminum heat exchanger with a corner that had been removed to show additional details.

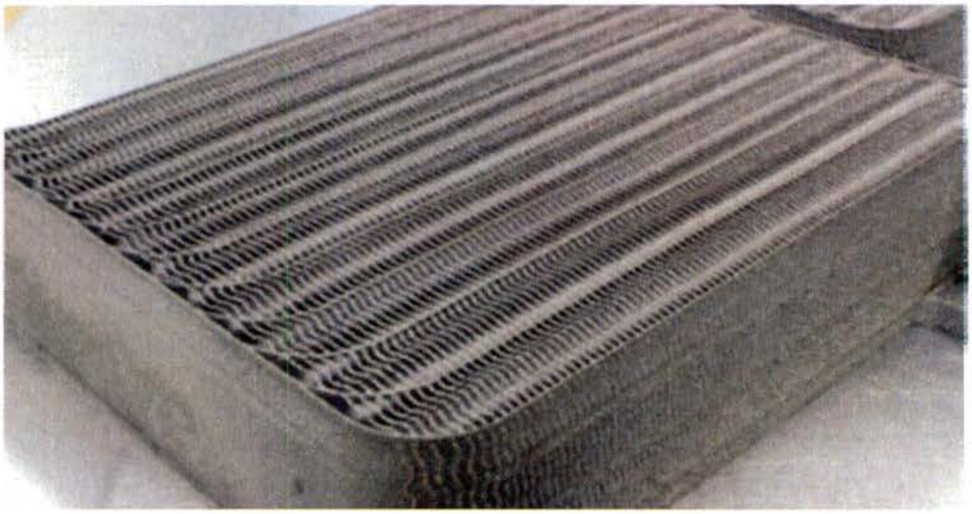


Figure 24. Photograph of the aluminum heat exchanger produced using additive manufacturing.

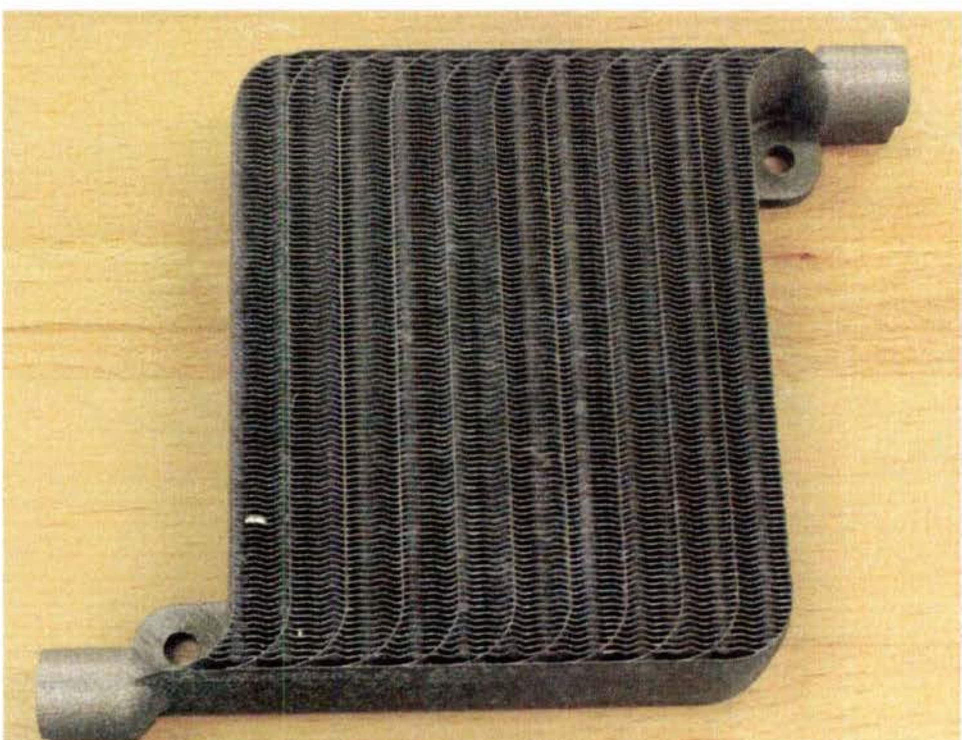


Figure 25. Another photograph of the aluminum heat exchanger produced using additive manufacturing.

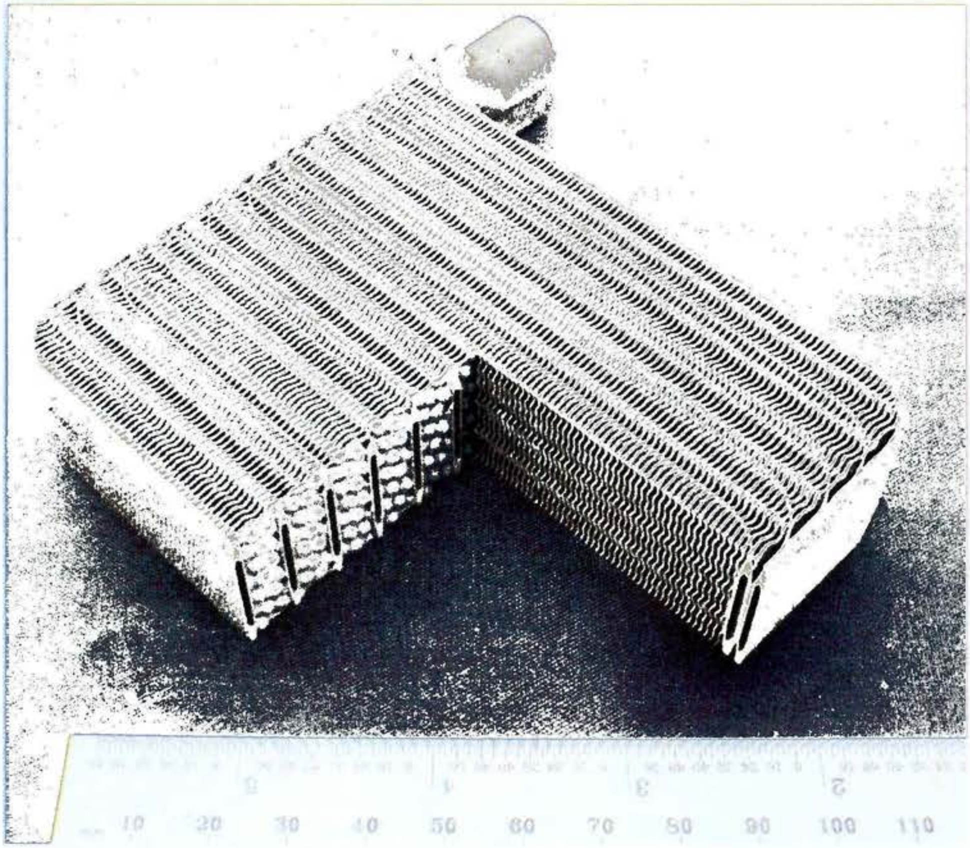


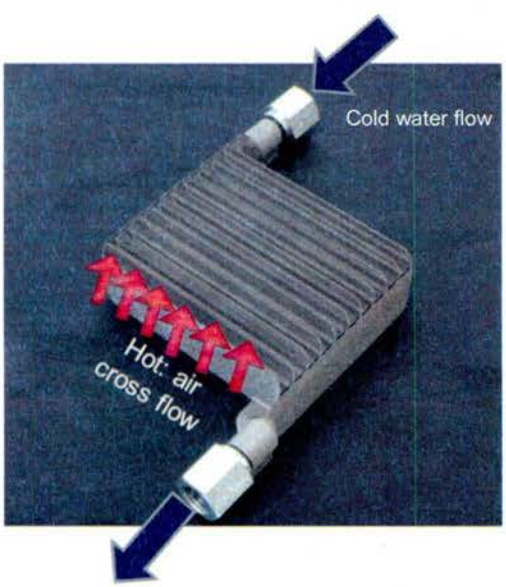
Figure 26. Photograph of aluminum heat exchanger design with corner section removed showing additional details.

## 7.0 Testing of Notional Heat Exchanger

Testing to ascertain the effectiveness for dissipation of heat by the notional heat exchanger built using additive manufacturing was conducted by Dr. Stephen Lynch and Shawn Siroka of the Mechanical and Nuclear Engineering Department of The Pennsylvania State University.

### 7.1 Testing Setup

The heat exchanger performance was determined by using the rate of heat transfer between hot and cold flow streams. This was conducted using the standard heat transfer rate of $\dot{m}c\Delta T$, where $\dot{m}$ the mass flow rate (kg/s), c is specific heat capacity (KJ/Kg-K), and T is temperature (K). By controlling the flow rate of both the hot and cold stream the performance could be determined in watts. These measurements may be used to calculate non dimensional heat exchanger parameters, which would enable a comparison with typical values from the literature. A basic schematic of the testing configuration and conditions are shown in Figure 27. Figures 28 through 30 represent photographs of the actual setup used in Dr. Lynch's heat transfer laboratory to evaluate the notional heat exchanger.




| **Cold Side** | **Hot Side** |
|---|---|
| Inlet Temperature ($T_{cold,inlet}$) | Inlet Temperature ($T_{hot,inlet}$) |
| Outlet Temperature ($T_{cold,outlet}$) | Outlet Temperature ($T_{hot,outlet}$) |
| Inlet Pressure ($P_{cold,inlet}$) | Inlet Pressure ($P_{hot,inlet}$) |
| Outlet Pressure ($P_{cold,outlet}$) | Outlet Pressure ($P_{hot,outlet}$) |
| Flowrate ($m_{cold}$) | Flowrate ($m_{hot}$) |

Figure 27. Basic schematic and conditions for testing configuration for measuring heat transfer capability of the notional heat exchanger.

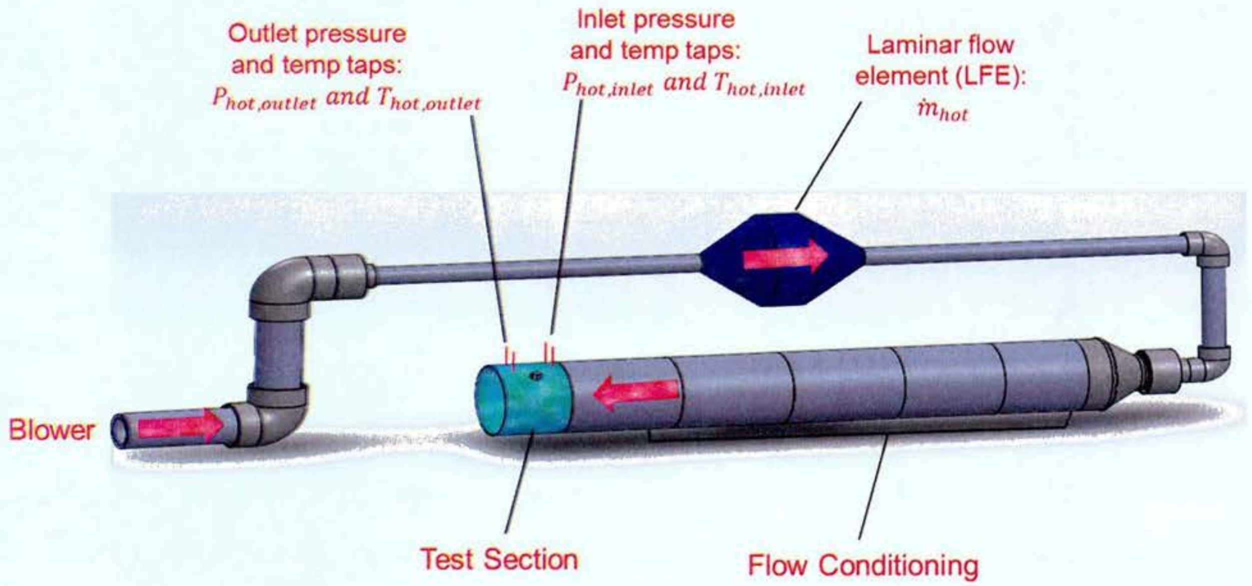



Figure 28. Arrangement of the heat transfer test chamber used to assess heat dissipation characteristics of the notional heat exchanger.

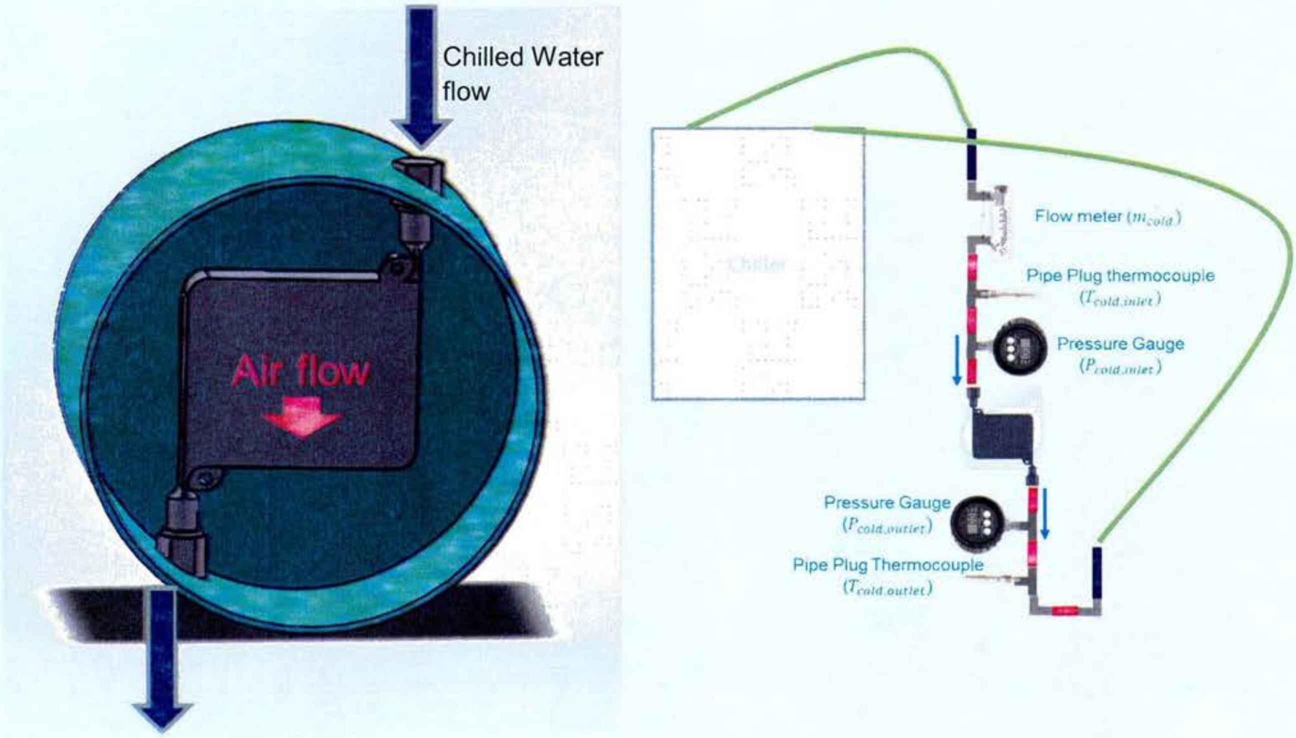



Figure 29. Schematic of the test cell for assessing heat dissipation characteristics of the notional heat exchanger.


Figure 30. Photographs of the test cell used to determine the heat dissipation characteristics of the notional heat exchanger.

The first stage for testing involved arranging flow within the hot air element. The laminar flow element (LFE) was place in-line in order to minimize turbulent flow. The heat exchanger was placed in the lower tube which is highlighted in green in Figure 30. This section of the tube had been fitted to hold the heat exchanger. It also has inlet and outlet pressure and temperature taps in order to track changes in response to the heat exchanger during testing. The heat exchanger was fitted inside of the large white pipe (shown to the left of Figure 30) using a polycarbonate insert. The polycarbonate insert was sealed within the pipe using a silicone sealant and was used to focus the air through the heat exchanger. Lastly, a recirculating system (shown in the right of Figure 30) was used to provide a mixture of chilled water-glycol. A flow meter was used to continually measure flow rate. The heat exchanger was instrumented with thermocouples and pressure gauges at the inlet and outlets to measure any changes in temperature and pressure during testing.

### 7.2 Testing Results

The results of changes in temperature and pressure of the water-glycol at the inlet and outlets during testing at two speeds of the blower used to circulate the hot air are shown in Table 3. These results indicated that heat exchanger was functioning effectively in cooling the hot air that was entering the heat exchanger. At the two blower speeds, the temperature of the air was decrease 15 °C and 18 °C, respectively.

Table 3. Results of water temperature and pressure measurements during testing.

10Hz Blower Speed

| Cold Side | | | Hot Side | | |
|---|---|---|---|---|---|
| Temperature inlet | C | 0.5 | Temperature inlet | C | 22 |
| Temperature outlet | C | 1.6 | Temperature outlet | C | 7.45 |
| Pressure Difference | Pa | 1378.95 | Pressure Difference | Pa | 0.1 |
| Mass Flow | kg/s | 0.026 | Mass Flow | kg/s | 0.001 |

20Hz Blower Speed

| Cold Side | | | Hot Side | | |
|---|---|---|---|---|---|
| Temperature inlet | C | 0.5 | Temperature inlet | C | 22.55 |
| Temperature outlet | C | 3.4 | Temperature outlet | C | 5.5 |
| Pressure Difference | Pa | 1378.95 | Pressure Difference | Pa | 10.1 |
| Mass Flow | kg/s | 0.026 | Mass Flow | kg/s | 0.005 |

Based on these results, important heat transfer parameters were established. The convective heat transfer parameters was found by using the area between the internal passages multiplied by the number of spaces. The Reynold's number was found by using the perimeter of the passages, which enabled the hydraulic diameter to be defined. The dimensions that were obtained are shown in Table 4, and the properties of the air and water-glycol mixture used for the calculations are shown in Table 5.

Table 3. Critical dimensions of the heat exchanger required for determining important heat transfer parameters.

| Properties | units | value |
|---|---|---|
| Length of internal passgage ways | m | 0.18542 |
| Area of crosssection_hot | m^2 | .000808 |
| Area of Crosssection_cold | m^2 | 1.2E-05 |
| Hydrolic Dyameter_hot | m | .013532 |
| Hydraulic Diameter_Cold | m | 0.001531 |
| Perimeter_hot | m | .23883 |
| Perimeter_cold | m | 0.03146 |

Table 5. Properties of the air and water-glycol mixture used for determining important heat transfer parameters.

| Properties | units | 10Hz | 2Hz |
|---|---|---|---|
| density of air | kg/m^3 | 1.2294 | 1.2313 |
| density of 25-75 water glycol | kg/m^3 | 1044.6 | 1044.4 |
| viscity of air (v) | m^s/s | 1.46E-05 | 1.46E-05 |
| viscousity of 25-75 water glycol | m^2/s | 3.49E-06 | 3.4E-06 |
| themal diffusity of air | m^2/s | 2.05E-05 | 2.04E-05 |
| thermal diffusivity of water glycol | m^2/s | 1.16E-07 | 1.16E-07 |
| thermal conductivity of air | (W/M-K) | 0.0253 | 0.0253 |
| thermal conductivity of waterglycol | W/(M-K) | 0.4456 | 0.4468 |
| specific heat air | J/(Kg-K) | 1.01E+03 | 1.01E+03 |
| specific heat water glycol | J/(Kg-K) | 3.68E+03 | 3.69E+03 |

The properties of the fluids that were used in the experiment were based on the average temperatures that were measured at the inlet and the outlet. The exact values for these properties were linearly interpolated using a Matlab code for each run. With the dimensions and fluid properties known, the Nusselt number, Reynolds number, Friction factor, and efficiency were calculated. The relationships used to determine these parameters are shown in Figure 31, and the graphical depiction of these results are shown in Figure 32.

Nusselt number (non-dimensional heat transfer): $Nu = \frac{q_{HX}}{A_{HX}\Delta T}\frac{D_h}{k}$

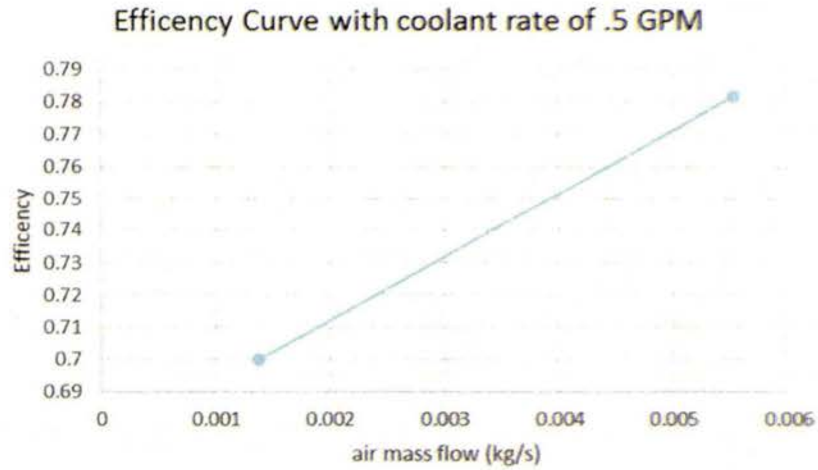
Reynolds number (non-dimensional flow): $Re_{Dh} = \frac{VD_h}{\nu}$

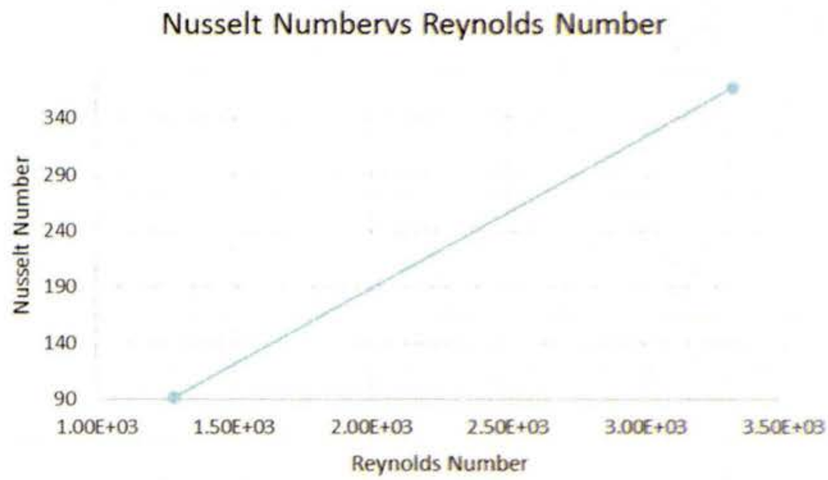
Friction factor (non-dimensional pressure drop): $f = \frac{\Delta P}{\left(\frac{\rho V^2}{2}\right)}\frac{D_h}{L_{HX}}$

Efficiency: $\varepsilon = \frac{q}{q_{max}}$ $where\ q_{max} = C_{\min}(T_{h,i} - T_{c,i})$

$A_{HX}$: heat transfer area (m^2)
$L_{HX}$: length of heat exchanger (m)
$D_h$: hydraulic diameter (m)
$V$: velocity thru HX (m/s)
$\rho$: density (kg/m^3)
$k$: thermal conductivity (W/m-K)
$\nu$: kinematic viscosity (m^2/s)
$q$: Heat transfer (W)
$C_{\min}$: heat capacity rate (J/sec-K)
$T_{h,i}$: Inlet Temp of heat side
$T_{c,i}$: inlet temp of cold side

Figure 31. Relationships used to calculate various parameters representing the heat exchanger.



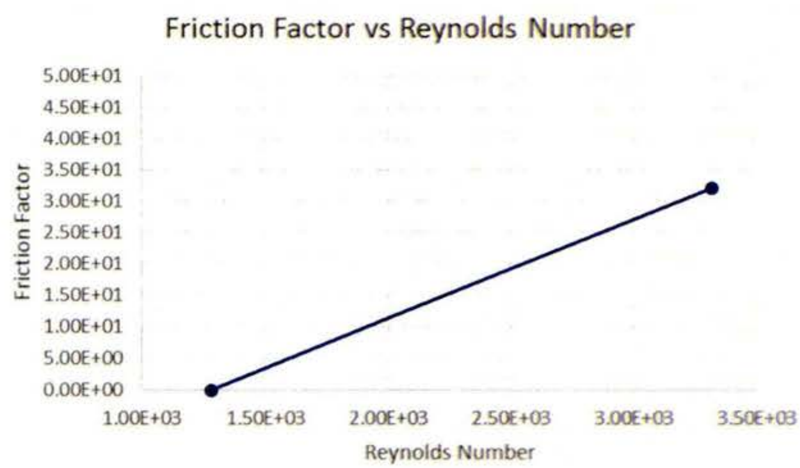




Figure 32. Graphical relationships obtained from the testing of the heat exchanger.

The first graph of Figure 32 shows effect of the heat transfer efficiency of the heat exchanger at the two gas flow rates used during testing. As expected, efficiency of heat transfer rate increases as air flow increases. The graph illustrates the effect of the Nusselt number based on Reynold's number and provides some indication of the effectiveness of the notional heat exchanger, since the Nusselt number is well above one for both testing points. The last chart in the figure shows that the friction factor representing the heat exchanger was negligible.

During testing, an infrared camera was also used to determine the uniformity of cooling within the heat exchanger. Images obtained by the infrared camera during testing is shown in Figure 33. The top image was obtained before water-glycol cooling had been initiated. Under this condition, it may be observed that temperatures are very uniform throughout the device. The bottom image was obtained after 30 minutes of cooling flow, which would be indicative of a steady state condition, and confirms that during operation the notional heat exchanger is functioning uniformly.

Valuable data was obtained during these tests that indicated the effectiveness of the notional heat exchanger. However, one problem was also identified during testing. After the two tests, a small leak was detected within the heat exchanger. Because the leak was internal to the complex fin and tube arrangement, it could not be rectified and resulted in termination of testing. Shown in Figure 34 is an infrared image of the heat exchanger indicating the location of the internal leak. As the leak developed, it also detrimentally effected the ability of the heat exchanger to cool uniformly.

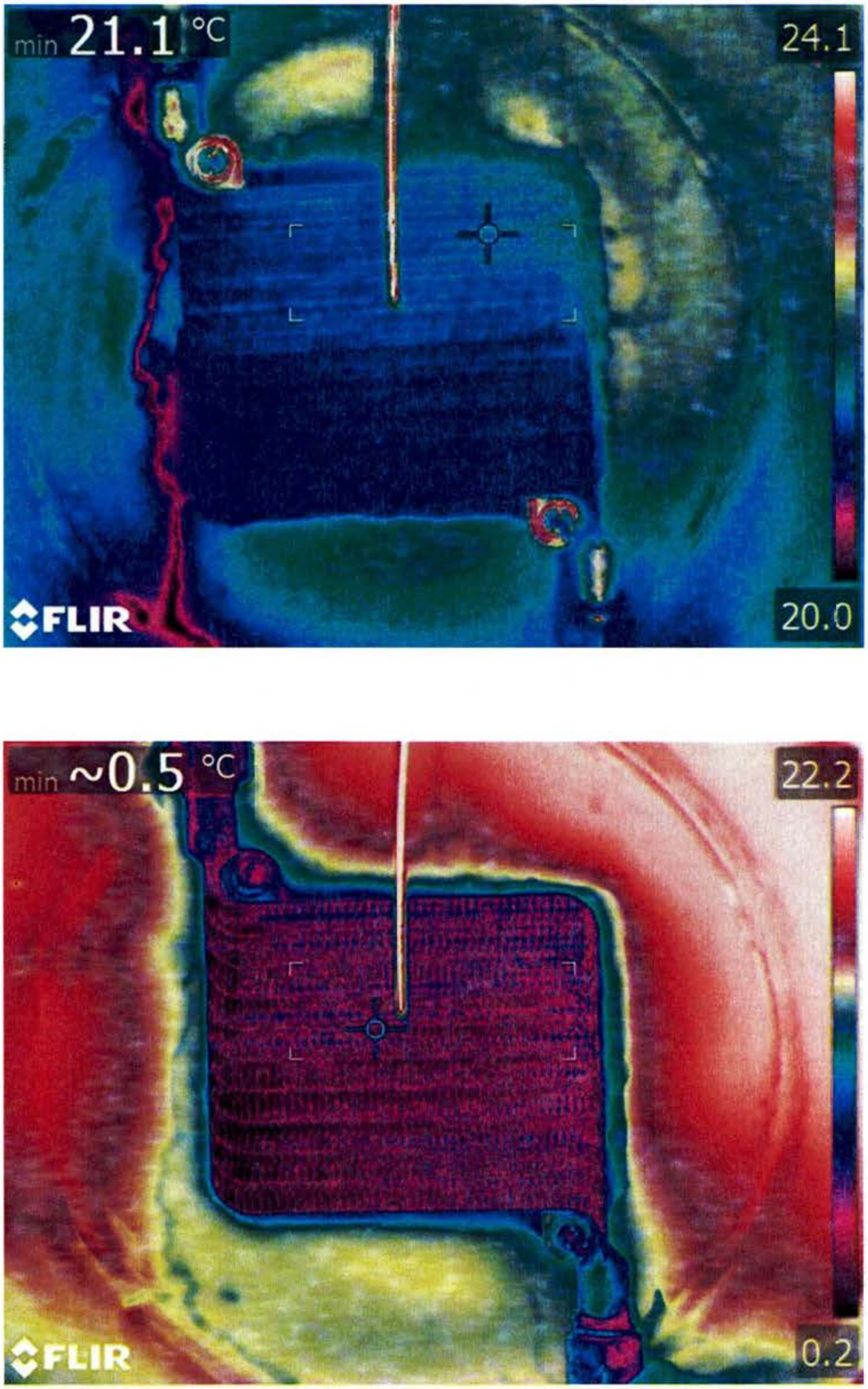



Figure 33. Infrared images of the heat exchanger obtained during testing but prior to flow of the water-glycol mixture (top) and after cooling flow for 30 minutes (bottom).

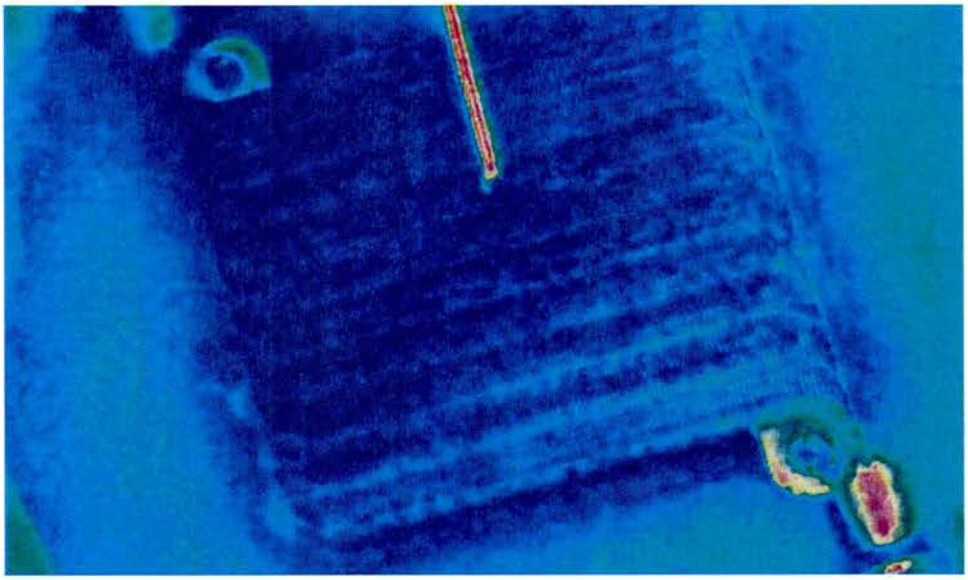


Figure 34. Infrared image of the heat exchanger during testing showing development of an internal leak which terminated testing.

## 8.0 Conclusion

Research was conducted at the Applied Research Laboratory and the Center for Innovative Materials Processing through Direct Digital Deposition at The Pennsylvania State University to determine the viability of additive manufacturing for producing aerospace heat exchangers for naval air platforms. A significant portion of this activity was directed at reviewing the basic requirements for heat exchangers and developing concepts that could result in an effective heat transfer device that would exploit the capabilities of additive manufacturing. During this effort, additive manufacturing equipment relevant to this applications was also reviewed and potential gaps were identified for impeding successful insertion of additive manufacturing for heat exchangers. This culminated in the selection of a concept and development of a full design based on producibility using additive manufacturing and the ability of the design to exploit the process for obtaining a highly functional heat exchanger. The full design was demonstrated in a manufacturing setting and the resultant notional heat exchanger was evaluated for performance.

The conclusions that may be drawn from this research are:

1. Additive manufacturing is being contemplated as a viable method to produce high value heat exchangers.

2. The interest in additive manufacturing for these devices is being based on the ability to produce highly complex shapes and features that are difficult to manufacture using traditional methods. Hence, Additive manufacturing for these applications may impact both performance and cost.

3. The additive manufacturing technique most applicable for producing these types of devices is the powder bed fusion process.

4. The maximum build size that is most available with today's powder bed fusion system is approximately 350 mm by 350 mm by 350 mm.

5. The process may be used to produce heat exchangers using aluminum alloys, stainless steels, and nickel-based alloys.

6. Although additive manufacturing, specifically the powder bed fusion process, shows significant promise for producing these products, the need to assure process reliability is seen as an impediment. Development and implementation of advanced sensing and control techniques are seen and an enabler for improving the reliability of the process and consistency of products that would be produced using the powder bed fusion process.

7. A notional part that was designed and built in an aluminum-silicon-magnesium alloy using the powder bed fusion process was able to achieve fine features and details inherent with this process.

8. The results of tests conducted to measure the heat dissipation quality of the notional heat exchanger indicated that the device provide very effective and uniform cooling. However, one defect was found in the notional heat exchanger that prevented extended evaluation. The defect was probably caused by improper fusion during building of the thin sidewall that represented the liquid cooling channel.

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